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Surface Wave Mode Coupling of Straight and Curved Dielectric Optical Waveguides

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Final Scientific Report on the Research Project entitled

SURFACE WAVE MODE COUPLING OF STRAIGHT AND CURVED DIELECTRIC OPTICAL WAVEGUIDES†

by

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Final Scientific Report

on

SURFACE WAVE MODE COUPLINGS OF STRAIGHT AND CURVED DIELECTRIC OPTICAL WAVEGUIDES

I. Introduction

The objective of this research project was to investigate, both theoretically and experimentally, the optical wave guiding properties of dielectric channels used in integrated optics. Our goal was to develop knowledge essential in specification, design and utilization of optical integrated circuits. More specifically it includes the development of

Guidelines for design of dielectric channel waveguides having desirable propagation, loss and radiation characteristics.

Guidelines for spacing two dielectric channel waveguides so as to avoid coupling between them, or for spacing so as to achieve controlled coupling if it is desired for circuit operation.

Guidelines for design of bends in dielectric channel waveguides so as to minimize the radiation loss by the bend, or to use the radiation from the bend in a controlled manner, if needed as part of a coupler or radiation element.

Design criteria for optical components such as directional couplers, isolators, channels, selectors, frequency selectors, etc.

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In the following section, we shall summarize specific studies that we have carried out during this investigation. This is followed by a list of publications and informations on personnel.

II. Specific achievements

1. Analytical Study on Radiation Loss of a Curved Waveguide Section

Work has been completed on the study of continuous radiation of the natural modes of a curved, homogeneous dielectric slab waveguide. It is found that, for a symmetric guide with a large radius of curvature, the phase velocity of a natural mode remains essentially the same as that of a straight waveguide, but additional attenuation of the waves occurs because of the radiation along the radial direction beyond the visual turning-point. Based on a mathematical theory called the Stoke's phenomenon, we have found that the distance between this turning-point and the waveguide surface can provide an adequate measure of loss due to the bend. For a bend in an asymmetric waveguide, attenuation of waves can be either reduced or enhanced, as compared to the symmetric case, depending upon the difference in penetration depths in regions exterior to the upper and lower waveguide surfaces. It is also found that substantial reduction in bending loss can be achieved by varying the refractive index of the media in the exterior region. The amount of radiation loss reduction for a truncated inverse-linear permittivity profile is then determined. Details of this work are discussed in reference 1.

Based upon the method we developed for slab waveguides, we have also investigated the radiation loss of a curved dielectric waveguide of an arbitrary finite cross-section. We believe we are the first to derive a general formula applicable to a waveguide with arbitrary transverse refractive index profile and of arbitrary cross-section. It was found that the attenuation constant of a surface-wave mode along a curved section increases exponentially as a function of the distance between the visual turning-point which is located in the forward direction in the cross-sectional plane, and the surface of the waveguide. Precise location of the turning-point however, depends upon the penetration-depth of the surface wave mode as well as the radius of curvature of the bend. Details of this work are discussed in reference 6.

2. Analytical study of radiation from a circular bend between two discontinuities in a dielectric slab waveguide:

In this work we are interested in the radiation of a surface-wave resulting from a bend through a small angle of an otherwise straight dielectric slab waveguide.

The radiated power and the radiation pattern have been studied theoretically. The configuration consists of two semi-infinite slabs joined by a circular bend. The results indicate that the discontinuities at the transitions between the straight slabs and the bend cause the radiation to differ significantly from the radiation of a bend of the same size but being part of a uniformly curved structure rather than being joined to two straight slabs.

The radiated power is found to vary inversely as the square of the radius of curvature, and the radiation pattern is composed of many closely spaced narrow lobes. As the radius of curvature of the bend increases the lobes become more numerous and more closely spaced. Details of this work are given in reference 5.

3. Numerical and analytical studies on modal characteristics of inhomogeneous, dielectric slab waveguides

A new numerical scheme based on invariant-imbedding for the study of the propagation characteristics of surface-wave modes in inhomogeneous slab-guides has been developed and programmed. This scheme involves only the numerical solution of a first-order Ricatti equation. Several different permittivity profiles were analyzed and convergence of the results to any desired accuracy was obtained. It was found that, for a nearly-symmetric waveguide structure, the cut-off frequency for the dominant mode of operation depends critically upon the extent of asymmetry. When the waveguide boundary varies from an abrupt junction between the guiding region and the surrounding substrate to a gradual transition, overlapping of the group velocities of different modes at some frequencies vanishes.

The numerical method devised for lossless slabs was extended for use on slightly lossy slabs and the results for both lossless and lossy slabs are used to investigate the behavior of pulses in such structures. It was found that the attenuation constant of a given surface-wave mode in a guide with an asymmetric structure depends quite sensitively upon the degree of asymmetry, and that it might prove feasible to adjust the attenuation through essentially non-loss related parameters of the guide.

The limitations of a widely used method for analyzing single-mode time dispersion of a pulse on a waveguide were pointed out. It was concluded that single-mode dispersion in a guide structure is actually not a problem, since attenuation will most always obliterate the signal before appreciable broadening occurs. Finally, the limitations on the use of slab-like structures due to spatial broadening effects were briefly pursued. Details of these studies are given in references 2 and 3.

4. Analytical study of surface-wave mode coupling of a system of parallel dielectric waveguides

In order to determine the significance of cross-talk between signals propagating in different waveguide channels, we have examined a number of different methods that are discussed in the literature for calculating the coupling between surface wave modes on parallel optical waveguides. We found them to give conflicting results for non-degenerate modes. A new variational formulation for the coupling coefficients was then derived and later extended in a straightforward manner to include anisotropic guides and/or an arbitrary number of guides or modes. The character of the differences between the various methods in the non-degenerate case were discussed, and the approximations required were investigated numerically for the case of two parallel slab waveguides. We have found that, in a situation in which significant power may be transferred between guided modes (that is to say for nearly-degenerate modes), all of the general theories (and those others capable of generalization) give the same results. However, our method seems to be more accurate in the calculation of a coupling between non-degenerate modes. We further extended the investigation to include losses in the waveguides and in the substrate. A general expression is then derived to determine the amount of isolation at any location along a pair of parallel waveguide channels. Details are given in reference 4.

5. Microwave modal study of dielectric optical waveguides

A model study of an optical thin-film waveguide in the microwave frequency range can provide more precisely-controlled measurements for the purpose of confirming the validity of corresponding theoretical solutions. An experimental study using 9.4 GHz was conducted. Such a signal is fed into a rectangular waveguide horn which flares from a standard X-band waveguide to a 25.4 cm by 0.95 cm multimode rectangular waveguide in order to provide controlled excitation at one end of a dielectric slab which is placed between two metallic parallel plates. The dielectric slab is made of polystyrene foam, which has a relative permittivity close to 1.03, following a logarithmic mixing rule, expressible in terms of the relative volumes occupied by the polyethylene and the trapped air. Thus, by compressing foam slabs of different initial volumes into slabs of the same volume, a different refractive index for each slab can be achieved. Slabs with slightly higher refractive index can then be used as the dielectric guides, as in the optical guiding structures. The use of foam material also provides an additional advantage in fabrication: design parameters such as cross-sections, spacings, and curvatures of straight and curved slabs can be met with precision. Experimental studies, such as power coupling between two guides, scattering pattern of curved guides at the bend, power loss due to continuous and scattering radiation in a curved section, etc., can be measured with a physical model closely identified with the theoretical one. Measurement of the field distribution was made with a miniature probe protruding from a slotted line placed on one of the metal plates, thus providing additional information on the detailed coupling mechanism in each case. Results of this experimental investigation are discussed in reference 7.

In summary, it is fair to say that we have completed a comprehensive study of the electromagnetic characteristics of dielectric slab waveguides, and have made substantial progress in channel waveguides of finite cross-section. However, a host of problems still must be understood before the use of integrated channel waveguides can be fully realized. Very important among these are the effect of discontinuities and other irregularities in wave guides, the role of anisotropic substrates and periodic structures, and the effect of the interface which separates the substrate from the upper half-space, etc.

Just recently, we have found that the interface effect can be utilized to support a substrate-attached mode in the case of a cylindrical conductor above a dissipative substrate. This mode is attenuated at a rate typically several times less than the conventional mode. We have not yet investigated the existence of the mode in a channel waveguide. This discovery was made near the end of the investigation, and a detailed evaluation of it must be deferred to a future investigation.

III. List of publications

Technical reports

1. E.F. Kuester and D.C. Chang, "Modal and Coupling Characteristics of Inhomogeneous Dielectric Slab Waveguides - Part I: Lossless Slabs," Scientific Report no. 1, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., Univ. of Colo., Boulder, Colo., July 1973.

2. D.C. Chang and F.S. Barnes, "Reduction of Radiation Loss in a Curved Dielectric Slab Waveguide," Scientific Report no. 2 prepared for AFOSR under Grant no. 72-2417, Univ. of Colo., Boulder, Colo., July 1973.

3. E.F. Kuester and D.C. Chang, "Modal and coupling characteristics of inhomogeneous dielectric slab waveguides - Part II. Lossy slabs and pulse dispersion," Scientific Report no. 7, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., Univ. of Colo., April 1974.

4. E.F. Kuester and D.C. Chang, "Non-degenerate surface-wave mode coupling of a system of dielectric waveguides," Scientific Report no. 9, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., University of Colo., Oct. 1974.

5. S.W. Maley, "Radiation from a circular bend between two discontinuities in a dielectric slab waveguide," Scientific Report no. 10, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., Univ. of Colo., Dec. 1974.

6. D.C.Chang and E.F.Kuester, "Propagation on a curved optical guide of finite cross-section," Scientific Report no. 11, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., University of Colorado, to be published in Feb. 1975.

7. H.A. Haddad, S.W. Maley and D.C. Chang, "Microwave modal study of optical dielectric slab waveguide," Scientific Report no. 12, prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., Univ. of Colo., to be published in Feb. 1975.

8. Edward F. Kuester, David C. Chang, Samuel W. Maley, "Modal and Coupling Characteristics of Inhomogeneous Dielectric Slab Waveguides," Prepared for AFOSR under Grant no. 72-2417, Electromagnetics Lab., Dept. of E.E., University of Colo., June 1973.

Papers published and to be published in journals and conference proceedings

1. E.F. Kuester and D.C. Chang, "Modal, dispersion and coupling characteristics of inhomogeneous dielectric waveguides," (accepted for publication in) IEEE Trans. Microwave Theory Tech., special issue on Integrated Optics, Vol. MTT-23, 1975.

2. E.F. Kuester and D.C. Chang, "Time and spatial dispersions of pulses in a dissipative, dielectric waveguide," submitted to IEEE Trans. Microwave Theory Tech. for publication.

3. E.F. Kuester, D.C. Chang and S.W. Maley, "Modal and coupling characteristics of inhomogeneous dielectric slab waveguides," MTT/IEEE International Microwave Symposium, IEEE Cat. no. 73 CHO 736-9 MTT,p. 22-24, June 1973.

4. E.F. Kuester and D.C. Chang, "Non-degenerate surface-wave mode coupling of a system of dielectric waveguides," 1974. International Union of Radio Science/ U.S. National Comm. (URSI) Annual Meeting, p. 177, Oct. 1974. (Copy of the digest is available from USNC/URSI, National Academy of Science, 2101 Constitution Ave., N.W., Wash. D.C., 20418).

5. S.W. Maley, D.C. Chang and H. Haddad, "Radiation from a bend in a dielectric slab waveguide," 1974 URSI/USNC Annual meeting, p. 178, Oct. 1974.

6. D.C. Chang, S.W. Maley, F. Barnes and H. Haddad, "Energy confinement in curved sections of dielectric waveguides," 1974 URSI/USNC Annual Meeting, p. 178, Oct. 1974.

7. D.C. Chang and E.F. Kuester, "Radiation loss of a surface-wave mode along a curved dielectric waveguide of finite cross-section," submitted for presentation in 1975 International Symposium on Antennas and Propagation, to be held at Urbana, Illinois in June, 1975.

Other publications

1. D.C. Chang, "Coupling and bends in dielectric waveguides," Lecture notes for a short course on Optical Communication via Glass Fiber Waveguides, sponsored by the Office of Telecommunication, U.S. Dept. of Commerce (OT/DOC), Boulder, Colo., Aug. 1974.

2. S.W. Maley, "Analog and digital techniques," Lecture notes for a short course on Optical Communication via Glass Fiber Waveguides, sponsored by the Office of Telecommunication, U.S. Dept. of Commerce (OT/DOC), Boulder, Colo., Aug. 1974.

3. F.S. Barnes, "Laser sources for communication," Lecture notes for a short course on Optical Communication via Glass Fiber Waveguides, sponsored by the Office of Telecommunication, U.S. Dept. of Commerce (OT/DOC), Boulder, Colo., Aug. 1974.

IV. List of personnel who participated in the research

1. Dr. David C. Chang, Associate Professor of Electrical Engineering
2. Dr. Frank S. Barnes, Professor of Electrical Engineering
3. Dr. Samuel W. Maley, Professor of Electrical Engineering
4. Mr. Edward F. Kuester, graduate student and research assistant (September 1972 - August 1974)
5. Mr. Hussain A. Haddad, graduate student and research assistant (September 1972 - August 1974)
6. Mr. Spence G. Bihler, graduate student and research assistant (January 1973 - June 1973)
7. Mr. L. Pizziconi, graduate student and research assistant (June 1973 - June 1974)
8. Dr. G. Bushnam, research assistant (Sept. 1972 - Nov. 1972).

V. List of dissertations

1. "Modal and dispersion characteristics of inhomogeneous, dielectric slab waveguide," by Edward F. Kuester, a M.Sc. Thesis, August 1974.

2. "Microwave modal study of optical dielectric waveguides," by Hussain A. Haddad, a M.Sc. Thesis (to be completed in Feb. 1975).

(In addition, we also expect the completion of a Ph.D. dissertation probably toward the end of 1975 by Edward F. Kuester on topics related to optical dielectric waveguides).

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13. ABSTRACT

Final scientific report on a research project entitled "Surface wave mode couplings of straight and curved dielectric optical waveguides." It includes a brief discussion of works completed on radiation loss of a curved waveguide section; radiation from a circular bend of an otherwise straight dielectric slab; modal characteristics of inhomogeneous guides; surface-wave mode coupling of parallel guides; and microwave modelling of optical waveguides.

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